ELECTROWEAK BARYOGENESIS IN THE MSSM

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Outline

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Based on work done in collaboration with:

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A. Riotto, M. Seco, I. Vilja, C. Wagner, F. Zwirner

INTRODUCTION

● Baryogenesis was proposed by A. Sakharov [a] as a mechanism to generate the baryon asymmetry of the Universe. The baryon-to-entropy Big-Bang Nucleosynthesis ratio (BAU)

$$\boxed{\eta_{BBN} \simeq (6 \pm 3) \times 10^{-11}}$$

● The three necessary conditions $\Longleftrightarrow$ are fulfilled by the Standard Model

- B violationg interactions $\Longleftrightarrow$ sphalerons (non-perturbative)
- C and $CP-$violation $\Longleftrightarrow$ CKM phase
- Out-of-equilibrium conditions $\Longleftrightarrow$ bubble formation

● This created a lot of excitement under the possibility of generating the baryon asymmetry at the electroweak phase transition, ELECTROWEAK BARYOGENESIS, (EWBG) and testing its implications at present and future colliders

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[a] A. Sakharov, JETP Lett. 6 (1967) 24

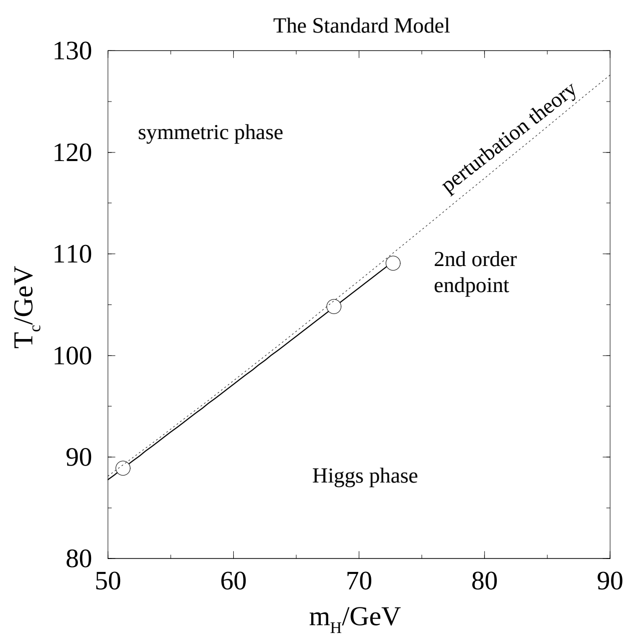
EWBG IN THE SM

● In the expanding wall the CP-violating background generates a CP-violating current that biases sphalerons to produce the BAU. In the SM CP-violation is too weak to generate enough BAU

● Once the BAU has been generated it must not be erased by sphalerons in the broken phase

$$\Longrightarrow \boxed{\frac{v(T_c)}{T_c} \geq 1}$$

● In the SM for $m_H > 80$ GeV the phase transition is not even first order [a]



[a] M. Laine, K. Rummukainen, hep-lat/9809045

THE STRENGTH OF THE PHASE TRANSITION IN THE MSSM

- In the MSSM the presence of light $\tilde{t}_R$ (with small mixing A_t) enhances considerably the strength of the phase transition [a]

$\Longrightarrow$ LIGHT STOP SCENARIO IN THE MSSM

- Two-loop corrections enhance the phase transition because of the strong coupling contributions [b]

- The phase transition is mainly controlled by the Higgs boson

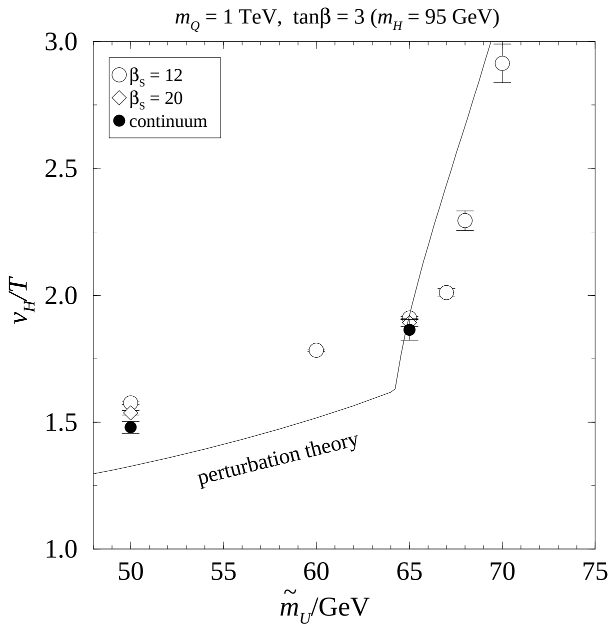
$\Longrightarrow$ LIGHT HIGGS BOSON

- The validity of perturbation theory confirmed by non-perturbative calculations [c]. In fact the phase transition is found in lattice calculations stronger than in the perturbative two-loop approximation by $\sim 15\%$

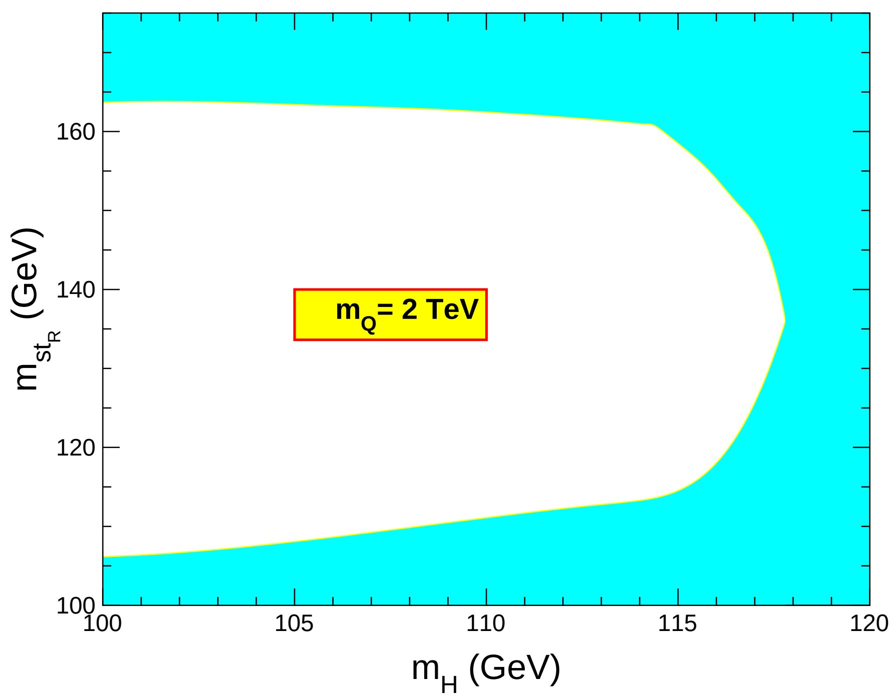
[a] J.R. Espinosa, M.Q., F. Zwirner, PLB307 (1993) 106; + A. Brignole, PLB324 (1994) 181; M. Carena, M.Q. and C. Wagner, PLB380 (1996) 81; D. Delepine, J. Gerard, R. Gonzalez and J. Weyers, PLB386 (1996) 183

[b] J.R. Espinosa, NPB475 (1996) 273;+ B. De Carlos, NPB503 (1997) 24; M. Carena, M.Q. and C. Wagner, NPB524 (1998) 3

[c] M. Laine, K. Rummukainen, hep-lat/9809045



- **Baryogenesis window** from two-loop approximation [a]



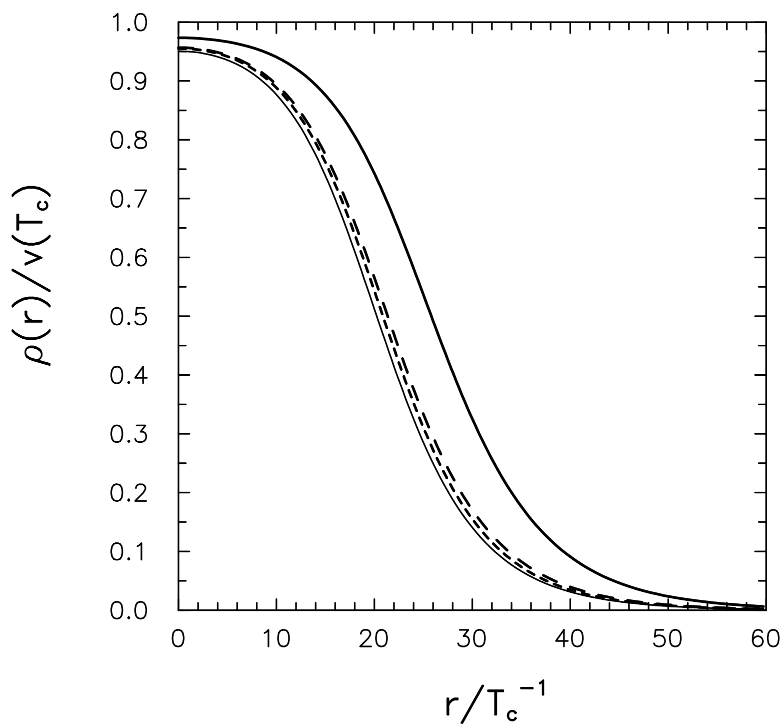
[a] M.Q. hep-ph/0101230

BUBBLES IN THE MSSM

- We have computed the bubble solutions of the MSSM [a] using the two-loop approximation for the effective potential. The main conclusions are:

- We have proven the goodness of the

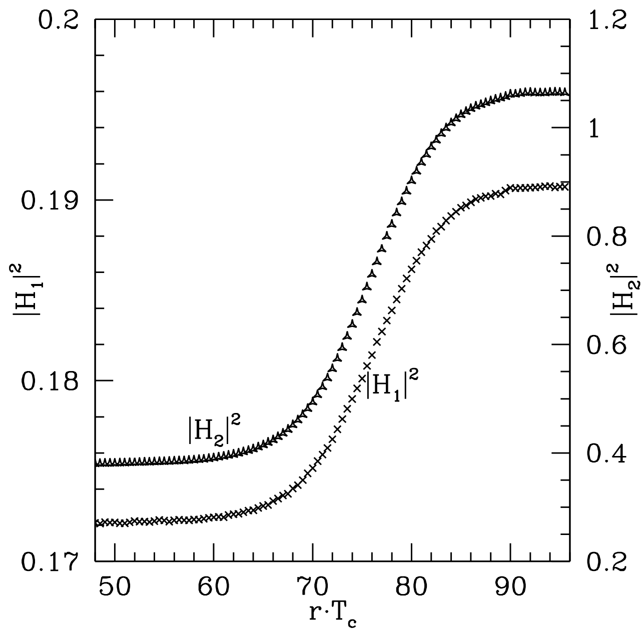
$\boxed{\text{THICK WALL APPROXIMATION: } L_\omega T_c \sim 20-30}$



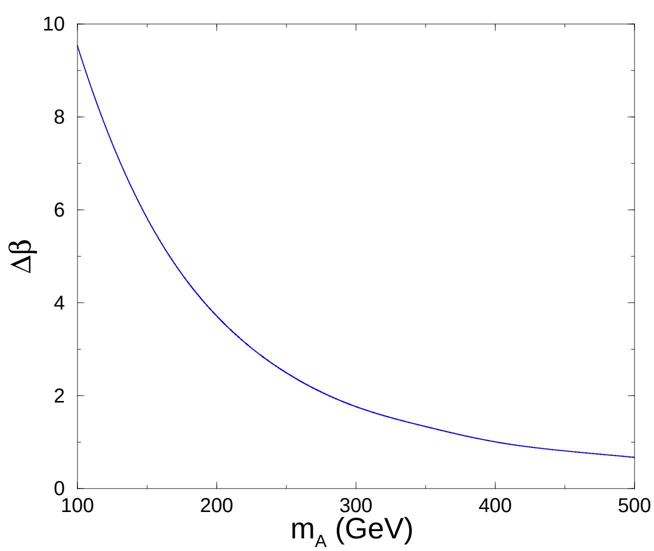
Plot of $\rho \equiv \sqrt{H_1^2 + H_2^2}$ for $m_Q = 1$ TeV, $\tan\beta = 2.5$, $A_t = 0$, $m_{\tilde{t}} = 150$ GeV, $m_A = 100$ GeV (thick), 200 GeV, 300 GeV and 400 GeV (thin)

[a] J.M. Moreno, M.Q., M. Seco, NPB526 (1998) 489

- Perturbative results confirmed by 4D lattice [a]



- We confirm the smallness of $\Delta\beta$ $\Rightarrow$ $\boxed{\Delta\beta \leq 10^{-2}}$



$\Delta\beta/10^{-3}$ for $M_2 = \mu = 0.2$, $A_t = 0.5$, $m_Q = 1.5$ TeV

[a] F. Csikor et al.hep-ph/0001087

CP-VIOLATING CURRENTS IN MSSM

- We derived a set of diffusion equations for particle densities induced by the passage of the wall of the expanding true-vacuum bubbles as

$$\boxed{-v_\omega n_i' + D_i n_i'' + \Gamma_{ij}\frac{n_j}{k_j} = S_i}$$

$n_i = n_Q, n_T, n_H, n_h$: $H, h = H_1 \pm H_2$

$' \equiv d/dz$: z=coordinate in bubble-wall frame

v_ω = bubble velocity

$k_B = 2$, $k_F = 1$: statistical factors

D_i= diffusion constants

Γ_{ij}=particle number changing rates: $\Gamma_Y, \Gamma_{ss}, \ldots$

S_i=CP-violating sources

- We have found [a] that the sources are given by

$$\boxed{S_i \simeq D_i (n_i'')^B}$$

n_i^B= Temporal components of the CP-violating currents j_B^μ induced in the Higgs background

- The currents j_B^μ in the MSSM are mainly induced by charginos and neutralinos.

[a] M. Carena, M.Q., M. Seco, C. Wagner, hep-ph/0208043

- We have computed the CP-violating currents for Higgsinos in the presence of a non-trivial background [a]

$$\boxed{\mathcal{M}_{\frac{1}{2}}(x) = \mathcal{M}_{\frac{1}{2}}(z) + (x-z)^\mu \partial_\mu \mathcal{M}_{\frac{1}{2}}(x) + \cdots}$$

- We resum to all orders in $\mathcal{M}_{\frac{1}{2}}(z)$ and keep derivatives to first order (derivative expansion)

- Resummation in $\mathcal{M}_{\frac{1}{2}}(z)$ smooths out a resonance effect when $M_2 \simeq |\mu|$ that appeared in our previous calculation, performed in the symmetric phase [b]

- The sources are found as

$$\boxed{n_H^B = \Im(M_2\mu)\,\{F_1(z)\gamma_-(z) + F_2(z)\gamma_+(z)\}}$$

$$\boxed{n_h^B = \Im(M_2\mu)\;F_3(z)\;\gamma_+(z)}$$

With $\gamma_\pm(z) = H_1(z)H_2'(z) \pm H_2(z)H_1'(z)$

- $\gamma_+(z) \propto \Delta\beta$. $\Longrightarrow \Delta\beta$ suppression. It contains the resonance enhancement

- $\gamma_-(z) \propto 1/\tan\beta$. No $\Delta\beta$ suppression. No resonance enhancement. Subleading effect.

$\Longrightarrow \quad \gamma_-(z)$ leading only for $m_A \to \infty$

[a] M. Carena, J. Moreno, M.Q., M. Seco, C. Wagner, NPB59 (1998) 273

[b] M. Carena, M.Q., A. Riotto, I. Vilja, C. Wagner, NPB503 (1997) 387

The baryon asymmetry

- The left handed density (chemical potential) $n_L \equiv \mu_L(z)T^2/6$ diffused from the bubble-wall (where there is CP-violating background) to the symmetric phase, induce a baryon asymmetry by the weak sphaleron effects Γ_{ws}

- The separation of effects of generation of n_L (with Γ_{ws} neglected) and of n_B (generated by Γ_{ws}) is justified by the smallness of Γ_{ws}

- Effective baryon density n_B in the broken phase is determined by solving the corresponding diffusion equation $(A \simeq 24/7)$

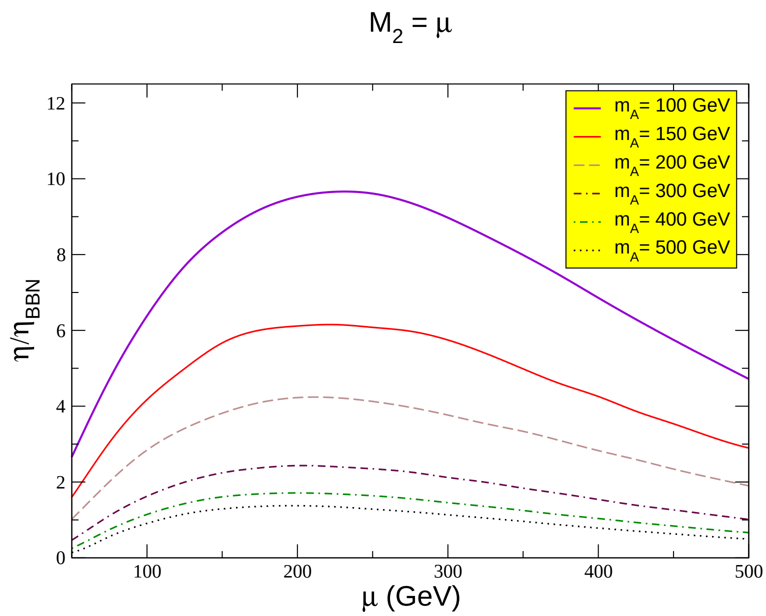
$$\boxed{n_B = -\frac{9 n_F \Gamma_{ws}}{2} \int_{-\infty}^{0} dz\, n_L(z) e^{A\Gamma_{ws} z/v_\omega}}$$

- We find enhancement for moderate values of m_A where $\gamma_-(z)$ dominates

- For $m_A \to \infty$ ($\Delta\beta \to 0$) the subleading effect $\gamma_+(z)$ dominates (numerically smaller)

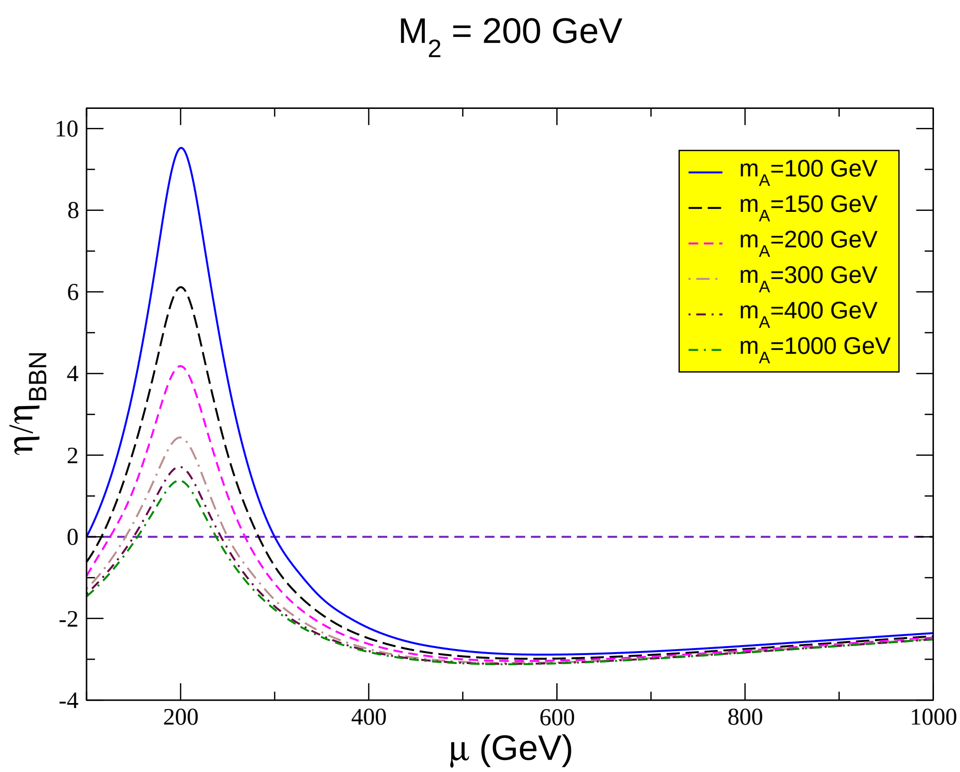
- Plots of η/η_{BBN} with $\eta_{BBN} = 6 \times 10^{-11}$

- Plot in the resonance region $M_2 = |\mu|$



We set $v(T_c) \geq T_c, m_h \simeq 115$ GeV, $m_Q \simeq 2$ TeV

- Away from the resonance



- The previous figures are done for $\sin\phi_\mu = 1$. For $\eta = \eta_{BBN}$ the required value of $\sin\phi_\mu$ is the inverse
- Taking into account the error in η_{BBN} and the uncertainties in the calculation one can set an absolute upper bound as

$$\boxed{\phi_\mu > 0.01}$$

- In general large CP-violating phases are consistent with electron and neutron EDM if first and second generation of sfermions are heavy:

$$\boxed{m_{\tilde{f}} > 1 \text{ TeV}}$$

- Two loop contributions [a] involving chargino loops and non-SM Higgs bosons jeopardize the latter scenario. These contributions are enhanced with $\tan\beta$ but become small rapidly with increasing m_A. In that case acceptable values of η can still be obtained for

$$\boxed{\phi_\mu > 0.1}$$

- Cancellation of EDM contributions is still possible and would soften some of the previous constraints [b]

[a] D. Chang, W. Chang, W. Keung, hep-ph/0205084

[b] T. Ibahim, P. Nath, PLB418 (1998) 98; M. Brhlik, G. Good, G. Kane, PRD59 (1999) 115004

COMPARISON WITH RECENT RESULTS

- Cline et al. [a], using semiclassical Boltzmann equations in the presence of forces induced by the CP-violating background, find that sources are $S_i \simeq D_i (n_i'')^B$. We find [b] equivalence between their formalism, and our formalism [c] where currents are induced from the CP-violating backgrounds. This is in contrast with previous approaches [d] where $S_i \simeq \Gamma_i n_i^B$ that would provide a two orders of magnitude enhancement

- We find [c] that $\gamma_-(z)$ does contribute to n_H^B in agreement with previous calculations [e]. $\gamma_-(z)$ was claimed not to contribute [a] by arguments based on extrapolations done in the absence of interactions with the plasma and in the mass eigenstates basis. Our explicit calculation does not confirm such cancellation

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[a] J. Cline, K. Kainulainen, PRL85 (2000) 5519; + M. Joyce, JHEP07 (2000) 018

[b] M. Carena, M.Q., M. Seco, C. Wagner, hep-ph/0208043

[c] M. Carena, J. Moreno, M.Q., M. Seco, C. Wagner, NPB59 (1998) 273

[d] P. Huet, A. Nelson, PRD53 (1996) 4578; M. Carena, M.Q., A. Riotto, I. Vilja, C. Wagner, NPB503 (1997) 387

[e] N. Rius, V. Sanz, NPB570 (2000) 155

CONCLUSIONS

The scenario of EWBG in the MSSM requires two general conditions

I. ENOUGH BAU IS PRODUCED

- Not too small CP-violating phases in the chargino sector. For m_A of the orden the electroweak scale v_{EW}

$$\boxed{\arg(M_2 \mu) > 0.01}$$

- Values of the chargino and neutralino masses of the order the weak scale

$$\boxed{M_2 \simeq \mu \simeq 100 - 300 \text{ GeV}}$$

- Heavy first and second generation sfermions from EDM constraints

$$\boxed{m_{\tilde{f}} > 1 \text{ TeV}}$$

- For large values of m_A, $m_A \gg v_{EW}$ larger phases are required

$$\boxed{\arg(M_2 \mu) > 0.1}$$

II. THE GENERATED BAU NOT ERASED AFTER THE PHASE TRANSITION

- This condition requires that the phase transition is strong enough first order for sphalerons to be out of equilibrium in the broken phase. We have found that this implies

$$\boxed{m_h \leq 117\,\mathrm{GeV}, \qquad m_{\tilde{t}} < m_t}$$

- The value of $\tan\beta$ should be large (to increase the Higgs mass)

$$\boxed{\tan\beta > 5}$$

- The value of m_{Q_3} should be large (to increase the Higgs mass)

$$\boxed{m_{Q_3} > 1 \text{ TeV}}$$

- The value of A_t not too small (to increase the Higgs mass) and not too large (to achieve $v(T_c) > T_c$)

$$\boxed{0.2\, m_{Q_3} < A_t < 0.4\, m_{Q_3}}$$

- Tevatron Run2 should find the Higgs and stops of the MSSM consistent with EWBG

TEVATRON WILL PROBE EWBG